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Research Article

Subcriticality control elements in a reactor system with an extended plasma source of neutrons with regard for temperature*

Vladimir V. Knyshev[1], Aleksandr G. Karengin[1], Igor V. Shamanin[1]

1 *National Research Tomsk Polytechnic University, 2 Lenin Ave., 634050 Tomsk, Russia*

Corresponding author: Vladimir V. Knyshev (vvk28@tpu.ru)

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Abstract

Materials have been selected for the shim rods and burnable absorbers to compensate for the excessive reactivity of the facility's blanket part and to provide for the possibility of reactivity control in conjunction with a plasma source of neutrons.

Burnable absorber is a layer of zirconium diboride (ZrB_2) with a thickness of 100 µm applied to the surface of fuel compacts. Boron carbide (B_4C) rods installed in the helium flow channels and used to bring the entire system into a state with k_{eff} = 0.95 have been selected as the shim rod material. Throughout its operating cycle, the facility is subcritical and is controlled using the neutron flux from the plasma source.

Verified codes, WIMS-D5B (ENDF/B-VII.0) and MCU5TPU (MCUDB50), as well as a modern system of constants were used for the calculations.

The facility's neutronic performance was simulated with regard for the changes in the inner structure and temperature of the microencapsulated fuel and fuel compact materials caused by long-term irradiation and by the migration of fission fragments and gaseous chemical compounds.

Keywords

Fusion-fission reactor system, plasma neutron source, criticality, burnable absorber, control and protection system

Introduction

High-temperature gas-cooled reactors (HTGR), due to the peculiarities of the core design composition and layout, feature advantageous characteristics in terms of nuclear safety and reliability (Alekseyev et al. 2015). In an HTGR, the power unit size is selected such that it would be possible to remove decay heat and to avoid the escape of fission products from the fuel into the coolant and then into the environment. These systems practically exclude the core melting, especially for cores composed of ceramics and graphite which are capable to withstand continuously temperatures in a range of 1000 to 3000 K (Alekseyev et al. 2005). No loss of coolant leads to an abrupt temperature growth which is explained by the core's high heating power. Using helium as the coolant excludes chemical

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reactions with the fuel and structural materials, and does not to lead to problems involving phase transformations (Grebennik et al. 2008). Besides, HTGRs have a high negative temperature reactivity coefficient (Alekseyev et al. 2005, 2015, Grebennik et al. 2008, Shamanin 2008), this ensuring the reliability of operation during transients and in power maneuvering modes.

Conventional reactor systems operate in a critical mode with the fission chain reaction controlled by influencing the balance of neutrons in the core's breeding environment. Operation of the facility under consideration, which consists of a blanket (the facility's energy generating part) and an external plasma source of fusion neutrons, differs from the traditional operating modes of the reactor, still the principle of control is basically the same and consists in influencing the balance of neutrons in the facility's active blanket part. The effective multiplication factor for the loaded blanket of the facility under consideration is made up for to the values 0.95 to 0.98 and is maintained at the preset level using criticality control elements and systems. The plasma source generates extra neutrons and ensures, in conjunction with the control system, safe operation of the entire facility (Arzhannikov et al. 2019a, Prikhodko and Arzhannikov 2020), improving so nuclear safety since, with this source being out of the generation mode, the whole of the blanket part will render deeply subcritical ($k_{eff} < 0.95$).

The efficiency of compensating systems depends on a number of parameters investigated by the authors in (Kalin et al. 2008, Rusinkevich 2016, Bedenko et al. 2019) and in other papers. Investigating the influence the changing thermophysical properties of the facility's blanket part have on its neutronic performance and the efficiency of the compensating system (Rusinkevich 2016, Bedenko et al. 2019) is of the utmost interest. Given these factors and the operating peculiarities of the subcritical facility under investigation, a vital objective discussed in this paper is to select the burnable absorber materials and to develop the shim rod (SR) model and layouts in conditions of long-term operation and high burn-up.

Materials and methods

Fig. 1 shows the layout of the facility under consideration (Arzhannikov et al. 2019a). Its active part's region adjoining the axis is substituted by a cylindrical vacuum chamber containing high-temperature plasma that generates extra neutrons as a result of D-D and D-T thermonuclear reactions. This plasma part has a chamber mated to it for injecting beams of high-energy neutral deuterium and tritium atoms (Anikeev et al. 2015, Yurov et al. 2016). The magnetic field in these two portions of the vacuum chamber, which contain high-temperature plasma, thermally isolates the plasma from the chamber walls in the radial direction (Arzhannikov et al. 2019). The parameters of the magnetic field and the plasma source of neutrons for making up the facility's blanket part, as well as the blanket configuration and composition are presented in (Arzhannikov et al. 2019, 2019a, 2020).

Structurally, the blanket consists of hexagonal graphite blocks having channels for the accommodation of fuel and injection (flow) of helium surrounded by two rows of graphite blocks which perform the reflector function. At the top and at the bottom, the blanket part is shielded with graphite blocks installed in one row. The fuel block has 76 small-diameter channels for fuel and seven large-diameter channels for helium. The width across flats is 0.207 m, and the height is 0.8 m. The graphite blocks that shield the blanket part at the top and at the bottom have a width across flats of 0.207 and a height is 0.3 m. The microencapsulated (coated particle) fuel for the graphite fuel compacts represents spherical kernels of $(Th,Pu)O_2$ with a diameter of 0.350×10^{-3} m covered with PyC and Ti_3SiC_2 layers of the thickness 0.90×10^{-4} m and 0.35×10^{-4} m respectively. The coated particle fuel is dispersed into the graphite matrix of the fuel compact to the surface of which an outer force coat of SiC is additionally applied. The fuel compact diameter is 10.17×10^{-3} m, the height is 20.10^{-3} m, and the thickness of the outer SiC layer is 0.3×10^{-3} m.

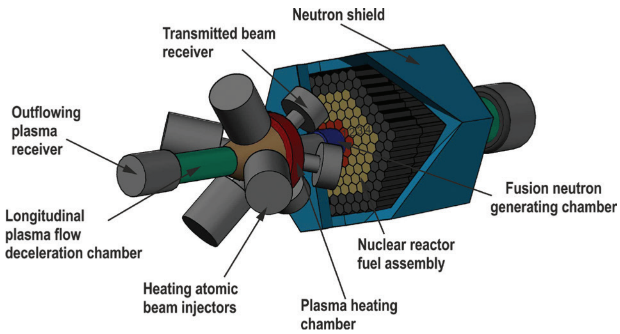

Figure 1. A subcritical facility with a plasma neutron source (Arzhannikov et al. 2019a).

Calculation of the temperature in the fuel compact

The BOL maximum fuel temperature was estimated based on a condition that there was bulk heat generation, $q_v(z,r)$, and surface heat generation, $q_s(z,r)$, in the fuel block. With the rated power of the facility being 60 MW, the maximum values $q_v^{max}(z,r)$ and $q_s^{max}(z,r)$ are respectively equal to 8.41×10^4 and 2.01×10^4 kW/m^3.

The computational studies presented in (Arzhannikov et al. 2020) show that the facility's fuel life, with a thermal power of 60 MW, is 300 eff. days. Such long-term operation leads to a major change in the coated particle fuel's nuclide composition and structure, the accumulation and migration of fission fragments and gaseous chemical compounds, and, as a consequence, to a change in the fuel's thermophysical properties (Bedenko et al. 2019) and temperature (Rusinkevich 2016).

A code, MCU5TPU (MCUDB50), is used to calculate the evolution of the fuel's nuclide composition and to estimate the radiation dose and the neutron fluence. The MCU-5 geometrical module makes it possible to simulate 3D systems with a geometry of any complexity when using a combined approach based on describing complex systems by combinations of elementary bodies and surfaces (MCU Project). The MCU-5 nuclide library includes an extensive list of isotopes and allows calculating the evolution of the nuclide composition and the criticality.

The effects of the fuel component's nuclide composition and the blanket part's thermophysical properties and temperature on the neutronic performance and efficiency of the compensating system have been calculated for an equivalent 2D cylindrical cell based on models in (Kalin et al. 2008, Hales et al. 2013, Degaltsov et al. 1987). These models make it possible to take additionally into account the mechanisms of the fission fragment diffusion and the migration of gaseous chemical compounds formed in the interaction of the oxygen released in coated particle fuel with fission fragments and the initial coat material. The migration and diffusion of fission products and the chemical compounds formed into the fuel compact matrix have been calculated with regard for the retarding capacity of the fuel kernel's principal diffusion barrier (Rusinkevich 2016, Ponomarev-Stepnoy et al. 2009).

Calculation of shim elements

The blanket part of the facility is a modified HTGR core with a neutron spectrum close to the epithermal spectrum. Compounds employed traditionally in high-temperature reactors (B_4C, B_4C-SiC, $Dy_2O_3TiO_2$, CrB_2+Al, Gd_2O_3, ZrB_2, AgInCd, Mo+Eu_2O_3, Hf-Zr, and others) were therefore used to select the effective materials for the shim rods (SR) and the burnable absorbers (BA) (Kalin et al. 2008).

Passive reactivity should be achieved with the use of SRs and BAs in conjunction with a plasma neutron generator which, together with the SR and BA system, is required to compensate for the effects caused by the nuclear fuel burn-up, and by the blanket slagging and poisoning in the process of the startup and during long-term operation. This was achieved in a 69-group diffusion approximation by the joint use of the WIMS-D5B (ENDF/B-VII.0) code (Pazirandeh et al. 2011) and an iterative method used to solve the neutron transport equation (Shamanin et al. 2017). The calculations take into account the effects leading to a change in the thermophysical properties of the blanket and in the temperature of the compact's fuel part.

After identifying the neutron absorbing material, which is effective in the operating neutron spectrum, the SRs and BAs are calculated. The best possible SR arrangement in the facility's blanket is also generated.

Results

Temperature calculation

The calculation, the results of which are presented in Figs 2, 3, has been performed for the facility's most heated fuel block as of the BOL. The outlet coolant temperature is limited to a value of 1300 K, and the permissible helium flow rate is 50 m/s. The temperature choice was not random since it is investigated if it is additionally possible to use high-temperature heat for implementing the technology of methane conversion to hydrogen.

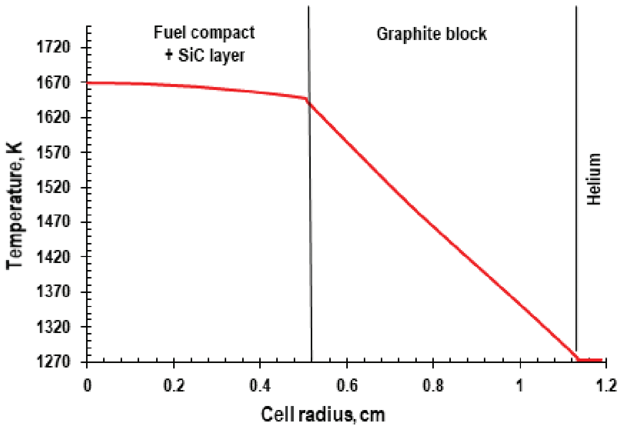

Figure 2. Temperature distribution by calculation cells.

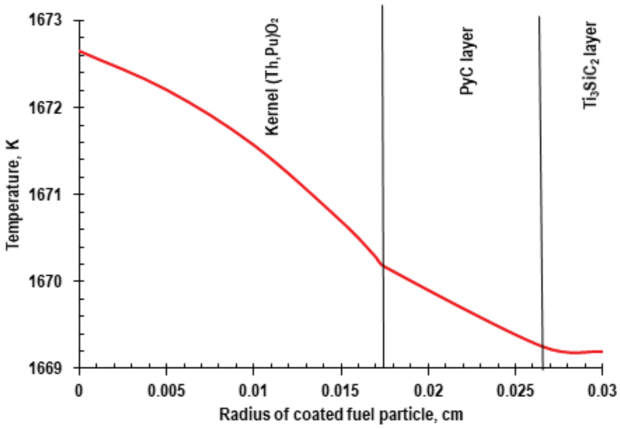

Figure 3. Temperature distribution in microencapsulated fuel.

The accumulation of fission fragments and gaseous compounds and the migration of these in conditions of long-term irradiation lead to a temperature growth in the kernel (Rusinkevich 2016, Hales et al. 2013, Degaltsov et al. 1987, Ponomarev-Stepnoy et al. 2009). As shown by the calculation results, the temperature in the kernels will grow by 40 K 1500 days after the facility startup. By the end of the fuel life, the temperature in the kernels will cumulatively increase by 70 K. Therefore, the SR and BA materials need to be selected with regard for structural and other changes leading a temperature growth and affecting the efficiency of the compensating system and the blanket's neutronic parameters.

The results of investigating the coated particle fuel and fuel compact materials have shown that the conditions of operation do not exceed the permitted working maximums (Degaltsov et al. 1987, Miller 1995) with the fast neutron fluence being ~ 1×10^{18} m^{-2}. In these conditions, the radiation changes in the kernel and in the coats are minor, and the strength characteristics of the main diffusion barriers are stable (Nappé et al. 2011, Katoh Yutai 2014). The additional safety barrier is formed by the graphite matrix and by the outer force coat.

Compensating materials and arrangement of compensating elements

An analysis of the findings has shown that the best reactivity compensation options are those with a ZrB_2 coat of the thickness $0.1\cdot10^{-3}$ m applied to the surface of the fuel compacts and with B_4C (Table 1) used as the SR material (Fig. 4). Table 1 presents the results of calculating the weight of the SR installed at the facility's center expressed in relative units. For comparison, Gd_2O_3 and Eu_2O_3 SRs of 0.01, 0.03 and 0.05 m in diameter have been calculated.

Table 1. Results of calculating the weight of one CPS rod

Material	k_{eff}, initial	k_{eff}, with rod	ρ of system	dρ (weight of one rod)
Rod diameter 0.01 m				
B_4C	1.207558	1.207012	0.171508	0.000375
Eu_2O_3	1.207558	1.207119	0.171581	0.000301
Gd_2O_3	1.207558	1.207235	0.171661	0.000222
Rod diameter 0.03 m				
B_4C	1.207558	1.205919	0.170757	0.001126
Eu_2O_3	1.207558	1.206108	0.170887	0.000996
Gd_2O_3	1.207558	1.206296	0.171016	0.000866
Rod diameter 0.05 m				
B_4C	1.207558	1.205016	0.1701355	0.001747
Eu_2O_3	1.207558	1.20537	0.1703792	0.001503
Gd_2O_3	1.207558	1.20542	0.1704136	0.001469

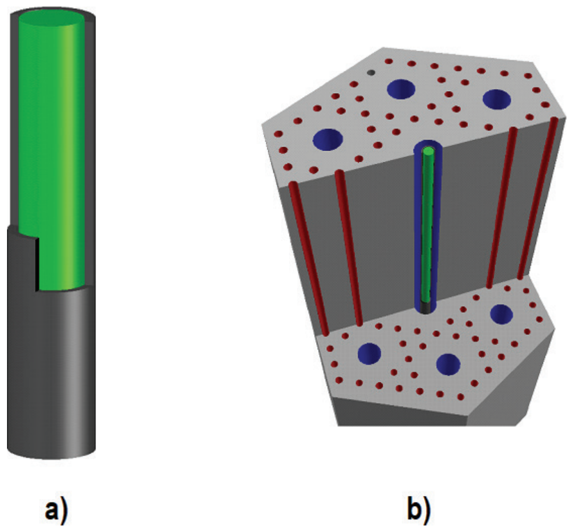

Figure 4. Model of the channel layout with a movable SR: a) – SR channel; b) – channel arrangement in the fuel block.

Using ZrB_2 makes it possible to reduce the effective multiplication factor to a value of $k_{eff} = 1.069833$. Further blanket subcriticality of up to $k_{eff} = 0.95$ was achieved using SRs of 0.01 m in diameter accommodated in the helium channels. The required number of rods is 138. The SR arrangement in the fuel block is presented in Fig. 4.

The SR channel material is steel of the KhN55M-VTs-VI(ID) (ChS57-VI(ID)) grade (Heat-resistant nickel-based alloy) which has proved itself to perform well in conditions of long-term in-pile irradiation.

Simulation of various options for the SR arrangement in blocks and for the block positions in the blanket made it possible to obtain the optimum SR arrangement presented in Fig. 5 (the figures show the fuel block row numbers). Therefore, the blanket's row 2 contains 10 blocks with fully loaded SRs, and row 4 contains 22 such blocks. There are 5 SRs installed in each block in the blanket's row 2, and there are 4 SRs installed in each block in row 4. Such arrangement leads to the effective multiplication factor reduced to approximately 0.9494, which corresponds to the required value for the facility operation.

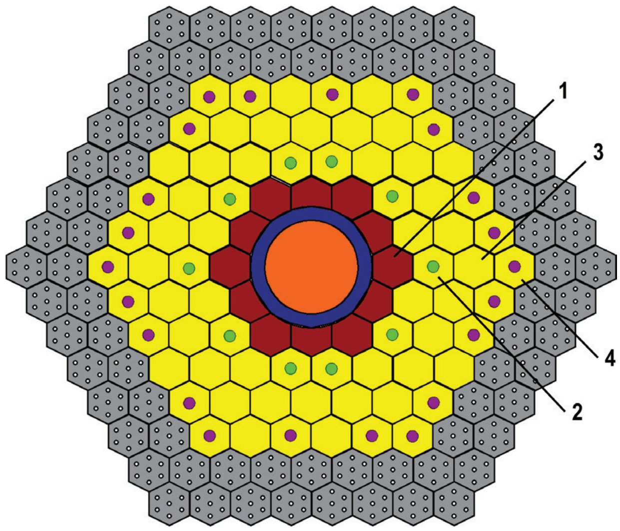

Figure 5. Arrangement of blocks with SRs in the facility's active part.

Discussion

The arrangement of fuel blocks with SRs shown in Fig. 5 allows reducing the material costs (the weight of the BAs for the SRs out of those considered in Table 1 is as small as possible), leveling off the power profile, and achieving the required subcriticality.

We shall note that the use of a plasma neutron source improves the facility's nuclear safety since switching off the injection of neutral atoms causes the generation of neutrons to drop by approximately a half for the initial 2.5 ms and by a factor of 20 more for the further 5 ms (Prikhodko and Arzhannikov 2020), that is, much faster than in the core of a traditional reactor.

Conclusion

The most advantageous method for reactivity compensation is to apply a ZrB_2 coat of the thickness $0.1\cdot10^{-3}$ m to the surface of the fuel compact and to use B_4C SRs of 0.01 m in diameter installed in the coolant channels. Coat application and sintered B_4C manufacturing technologies are successfully developed by research teams at the Tomsk Polytechnic University.

The burnable absorber and shim rod materials have been chosen with regard for the changes in the inner structure of the microencapsulated fuel and the fuel compact caused by long-term irradiation and by the migration of fission fragments and gaseous chemical compounds affecting the thermophysical properties and the temperature of the compact's fuel part.

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